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MODEL TESTS OF INFLATABLE LIFE RAFTS IN BREAKING WAVES

CAROL L. HERVEY

U.S. Coast Guard
Research and Development Center
Avery Point
Groton, CT 06340-6096

DONALD J. JORDAN

Consulting Engineer
Glastonbury, CT 06033

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SAMUEL F. POWEL, III
Technical Director
U.S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340-6096

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16. Abstract

Model tests were conducted to investigate the capsizing of inflatable life rafts when struck by a breaking wave. The life raft models were tested with and without water ballast compartments. Three configurations of water ballast compartments were evaluated; four rectangular bags arranged symmetrically on the bottom of the raft, a single toroidal bag, and a single hemispherical bag.

The unballasted raft was consistently capsized. The ballasted rafts were not capsized with any of the three ballast configurations.

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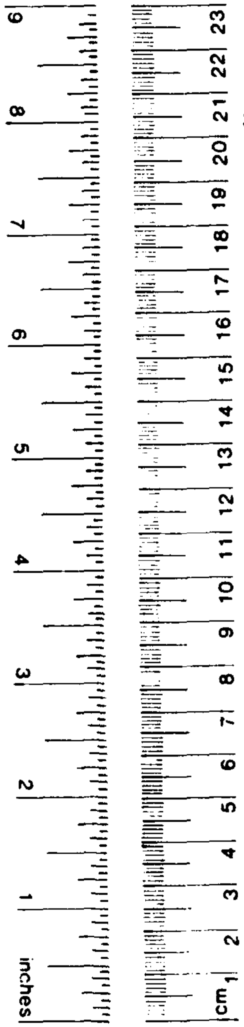
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

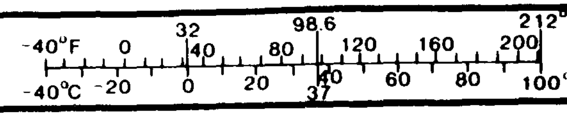
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

Modern inflatable life rafts intended for use on the ocean are generally equipped with water ballast compartments. These compartments consist of a bag or bags of various shapes attached to the bottom of the raft and provided with openings so that the bags rapidly fill with water when the raft is deployed. These water-filled bags greatly increase the stability of the raft. Full-scale experience and model testing (Reference 1) clearly show that water ballast compartments significantly reduce the probability of capsize under storm conditions.

The water ballast compartments on inflatable life rafts currently offered for sale differ in volume and geometry with each manufacturer. It is the purpose of these tests to investigate the effect of ballast configuration on capsize vulnerability under breaking wave conditions. In the model tests reported in Reference 1 rigid shapes were used to simulate the water-filled bags. For these tests the bags were constructed of a thin flexible latex material which permitted the bags to deflect under load and thus provide a more realistic simulation of the behavior of full size equipment.

In the Reference 1 tests, inflatable life rafts with or without water ballast compartments were not capsized by non-breaking waves even though the waves were steeply crested and the raft was exposed to high surface winds. This characteristic behavior was confirmed in exploratory testing prior to the start of these tests.

For all the tests reported here a breaking wave of a consistent shape and size was used to evaluate the life raft capsize characteristics. Tests were conducted with and without a surface wind.

TEST FACILITY

The facility used for this investigation is capable of generating a single breaking wave with a height of 1.7 ft. (0.5 m) and a wave speed of 10.8 ft/sec (3.3 m/sec). For a 1/13 scale 6-person life raft model, this test wave represents a 22 ft. (6.7 m) full-scale storm wave. For a 1/10 scale model the wave represents a 17 ft. (5.2 m) wave. The form of the wave is such that the breaking crest contains a large mass of water moving at wave speed thus the wave is believed to represent a very dangerous type of storm wave. For certain tests air was blown over the surface of the wave at a velocity which would simulate 75 to 90 mph (120 to 145 km/hr) full scale.

The configuration of the wave tank is shown on Figure 1. The tank is 32 ft. (9.8 m) long and 3 ft. (0.9 m) wide. For these tests the water depth was maintained at 2 ft. (0.6 m). The energy for generating the wave was obtained from a column of water

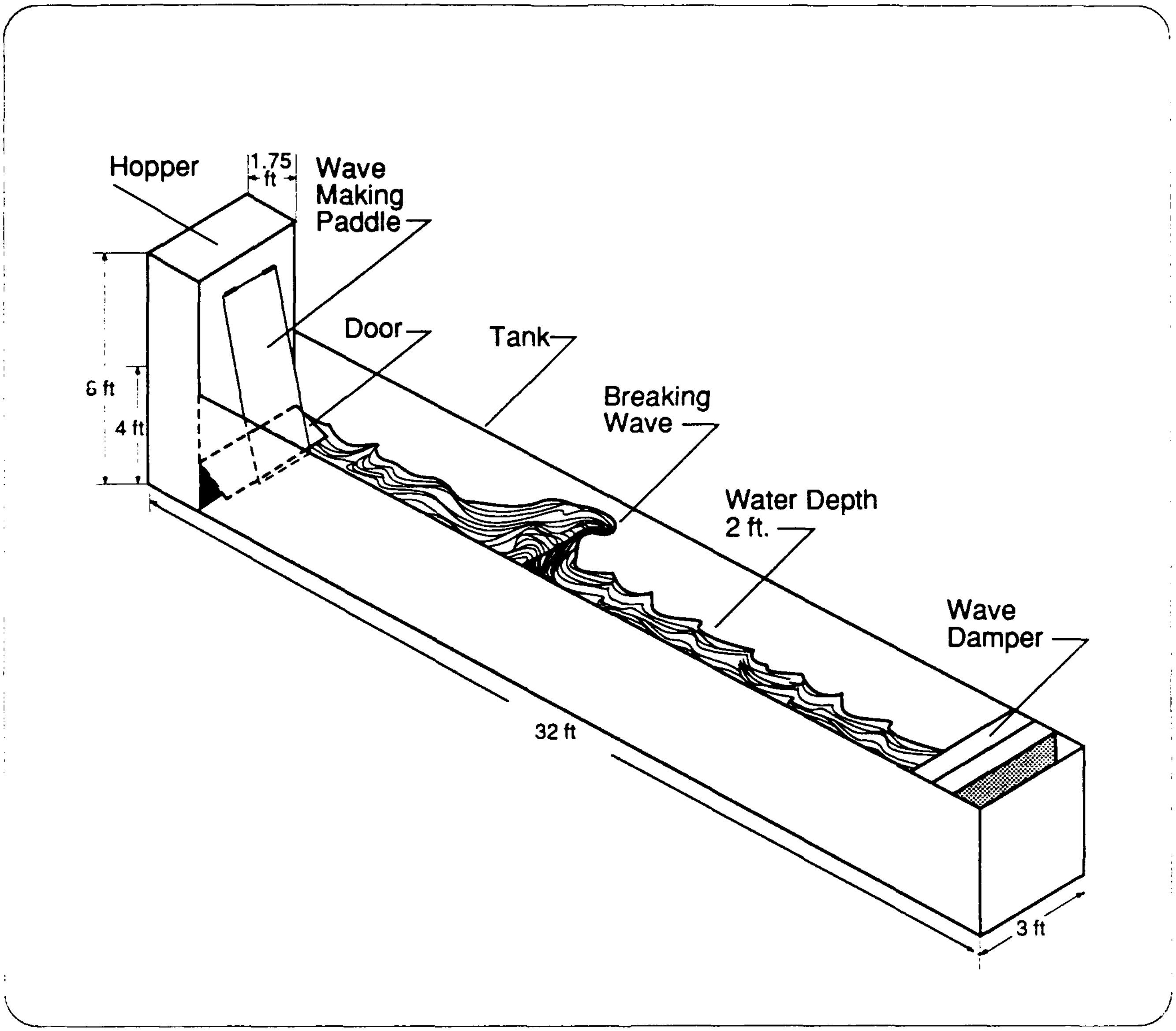


FIGURE 1. Breaking Wave Tank

contained in a hopper located at one end of the tank. A large door is provided in the lower part of the hopper. This door is equipped with a quick action latch so that the contents of the hopper can be quickly dumped. As shown in Figure 1, as the door opens it bears against a large paddle which in turn generates the breaking wave. The shape and size of the wave can be altered by varying the height of water in the hopper and by changing the geometry of the paddle. The facility is simple and inexpensive to operate. It can generate a highly reproducible breaking wave.

To simulate storm conditions wind was blown over the surface of the breaking wave for part of the testing. A 5 hp blower was used to generate the wind. The velocity pattern of the air downstream of the discharge nozzle was surveyed with a hand-held meter and the location of the nozzle relative to the breaking wave crest was selected to provide a local velocity of 25 mph (40 km/hr) at the appropriate position in the tank as shown on Figure 2 and Figure 3.

Twenty-five mph (40 km/hr) wind at model scale corresponds to a full-scale velocity of 79 mph (113 km/hr) for the 1/10 scale model and 90 mph (145 km/hr) for the 1/13 scale model. For some of the tests the blower nozzle was lowered to provide even a higher air velocity at the test section.

MODELS

The models used in these tests are intended to be representative of inflatable life rafts in general rather than any specific manufacturer's design. They are the same configuration but different scale from those tested in Reference 1. The proportions of the raft are based on the U.S. Coast Guard capacity requirements, Section 160.051-4(i) of Reference 4. There must be 4 sq. ft. (0.4 sq. meters) of clear inside area and 3.4 cu.ft. (0.1 cu. meters) of volume in the inflated tubes per person. The overall diameter, D, and the tube cross section diameter, t, can then be related to the capacity, P, by the relation:

$$4P = \frac{\pi (D-2t)^2}{4} \quad \text{and} \quad 3.4P = 2\ \pi^2\ (D-t)\ (t^2/4)$$

Solution of these equations for a 6-person capacity raft indicates an 86 in. (218 cm) overall diameter and 10 inch (25.4 cm) tube diameter.

Two models of this 6-person raft were tested, a 1/13 scale model with a diameter of 6.6 inch (16.8 m) and a 1/10 scale model with a diameter of 8.6 inch (21.8 cm). The models were constructed of balsa and plywood with the exception of the ballast bags which were constructed of .018-inch latex (0.46 mm). From observations of the behavior of full-scale rafts in storm conditions it was noted that the raft structure, which consisted

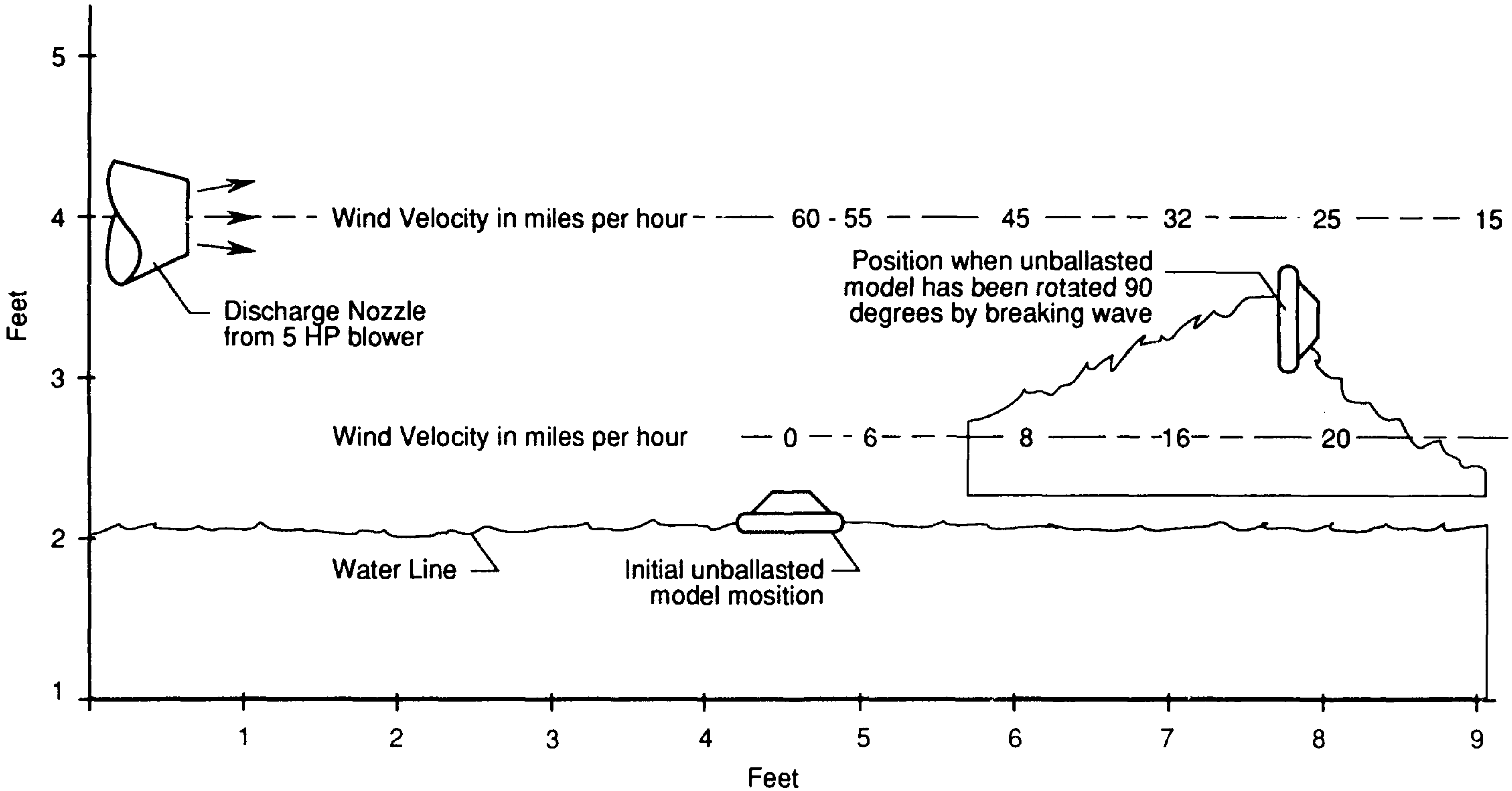


Figure 2. Wind Generator Installation

FIGURE 3. Wind Generator Installation

of two inflatable tubes bonded together, did not appear to experience deformations large enough to affect the dynamic performance. Therefore it was considered acceptable to make the raft model rigid. On the other hand, the water ballast compartments for full-scale rafts have no structure other than the bag membrane. It seems highly probable that during a breaking wave strike deflection of the water ballast compartments would have an important influence on the dynamic performance of the raft. Therefore it was decided that the model should be provided with flexible water ballast compartments. To give the correct structural scaling the model ballast compartment material should be very flexible. This requirement led to the use of .018-inch (0.46 mm) latex. The desired shapes were obtained by building forms, shown on Figure 4, and dipping the forms into a liquid latex solution.

Figure 5 shows the dimensions of the raft models with no ballast compartments attached. The 1/13 scale model weight of 5.3 oz. (150 gr.) simulates a 6-person raft with 3 occupants. The 1/10 scale model weight of 14.6 oz. (414 gr.) simulates a 6 person raft with 5 occupants.

Three types of water ballast compartments were tested. They are representative of the current products of representative life raft manufacturers:

1. Four rectangular bags distributed symmetrically on the bottom of the raft.
2. A single toroidal shaped bag.
3. A single hemispherical bag.

Models of all three types were constructed of molded latex in 1/13 and 1/10 scale. The life raft models were configured so that they could be tested with no ballast or with any of the three types.

In 1985 the Coast Guard issued a notice of Proposed Standards For Improving Liferaft Stability (Reference 2). This document specified that the total volume of water-filled appendages must not be less than the volume of the principal buoyancy compartments of the life raft. This requirement was used to establish the volume of the four bags used for these tests. The toroidal bag and the hemipherical bag dimensions were made essentially the same as those tested in Reference 1 except for scale. Dimensions and photographs of the ballast compartments are shown on Figure 6 and Figure 7. A series of 1/4 in. (6.3 mm) holes in the walls permitted the compartments to fill with water. A check was made before each test to insure that they were in fact full.

INSTRUMENTATION

The behavior of the models when struck by the breaking wave was recorded with a video camera at 60 frames per second. A grid

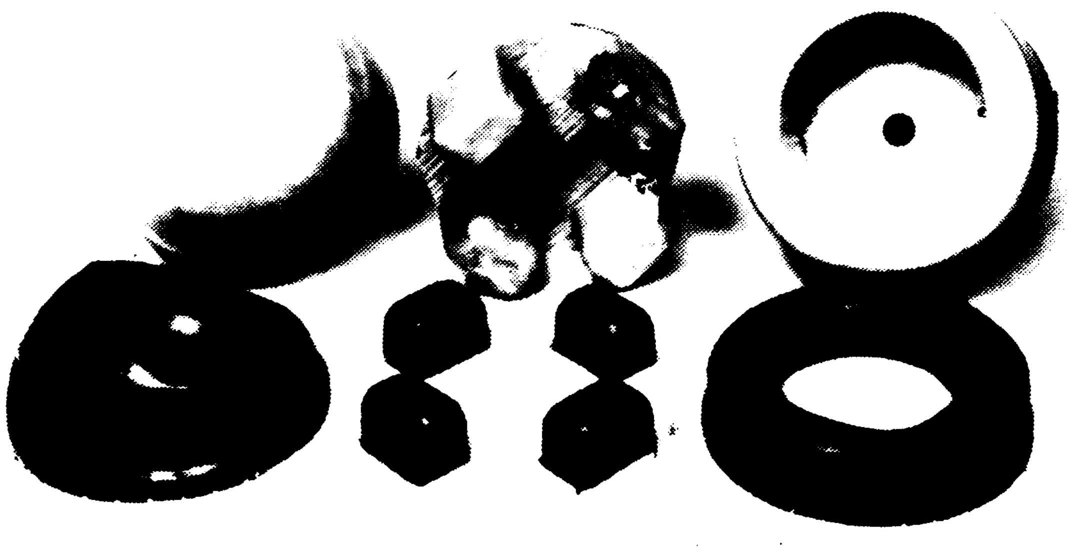
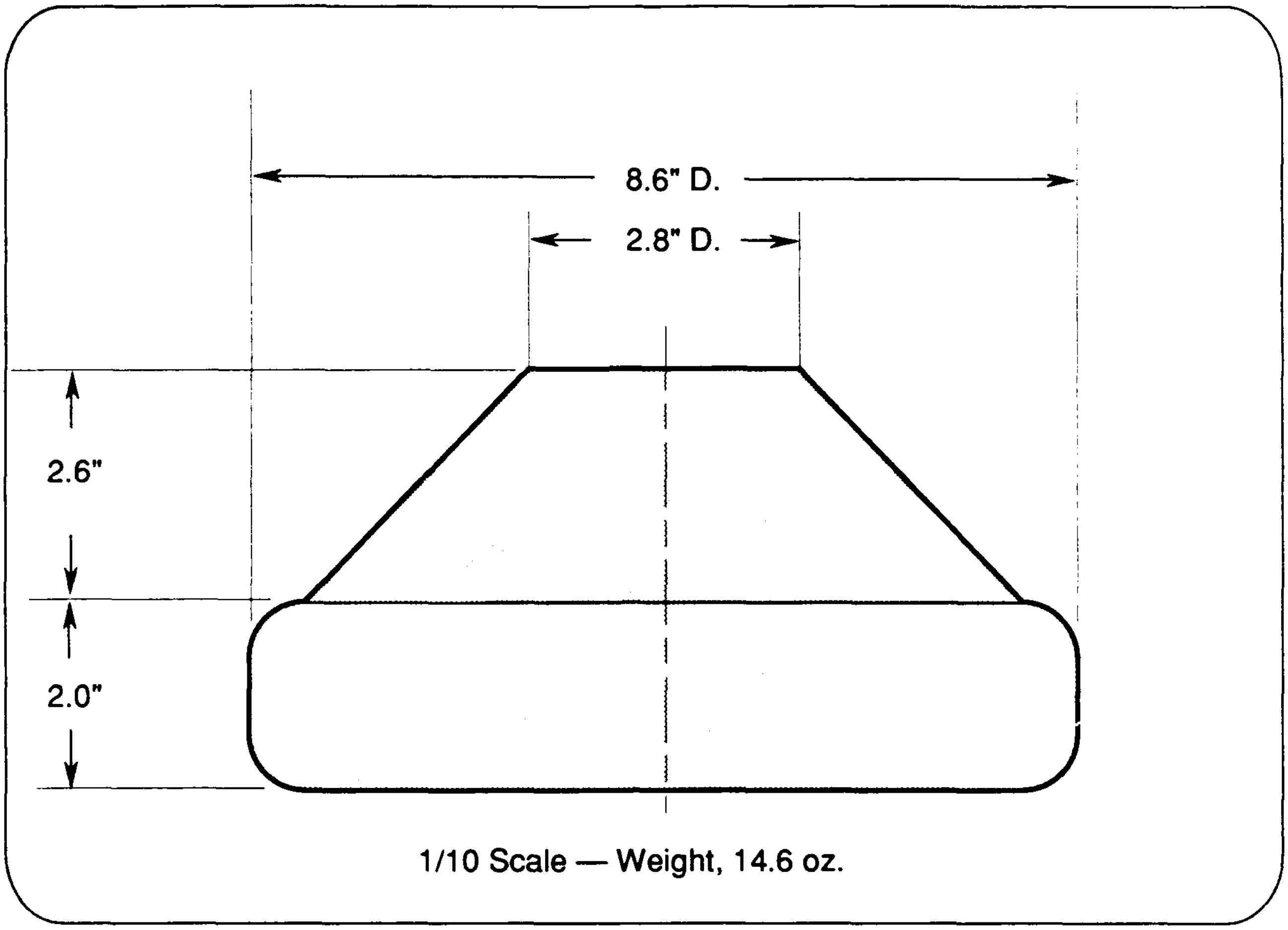


FIGURE 4. Forms for Molding Latex Ballast Compartments



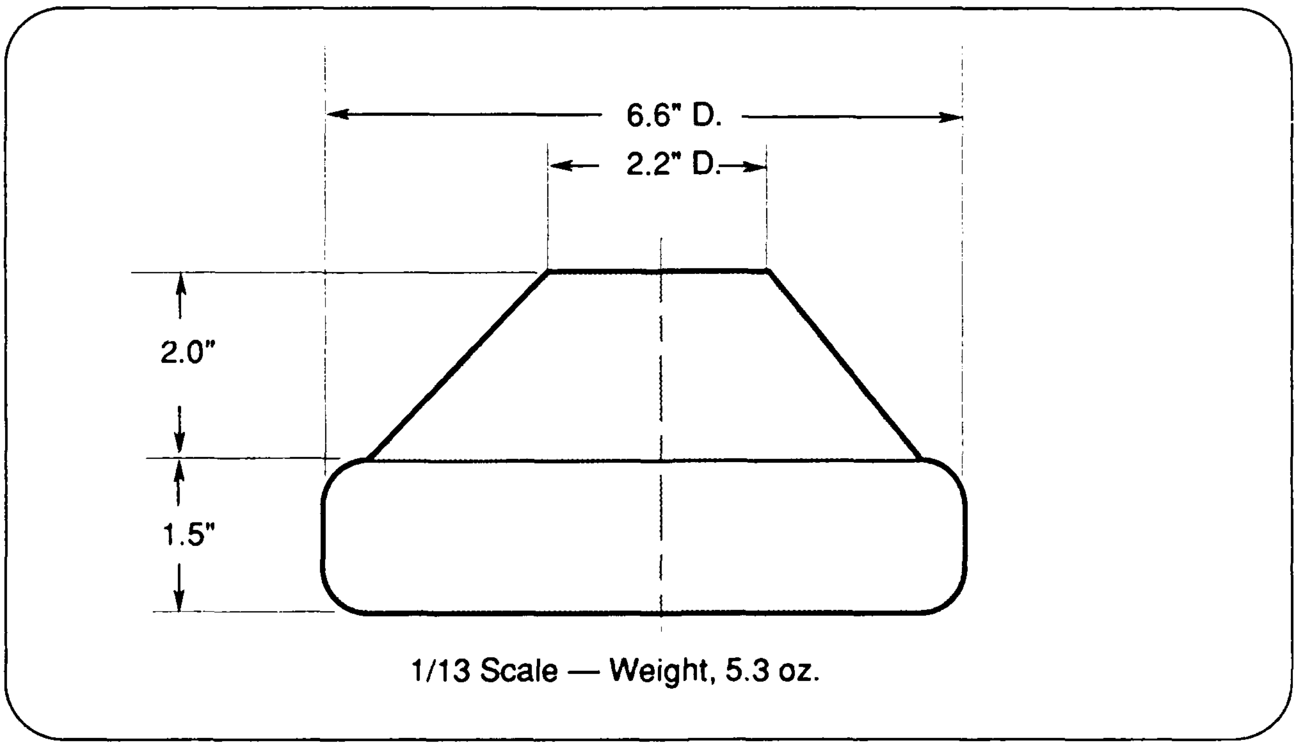
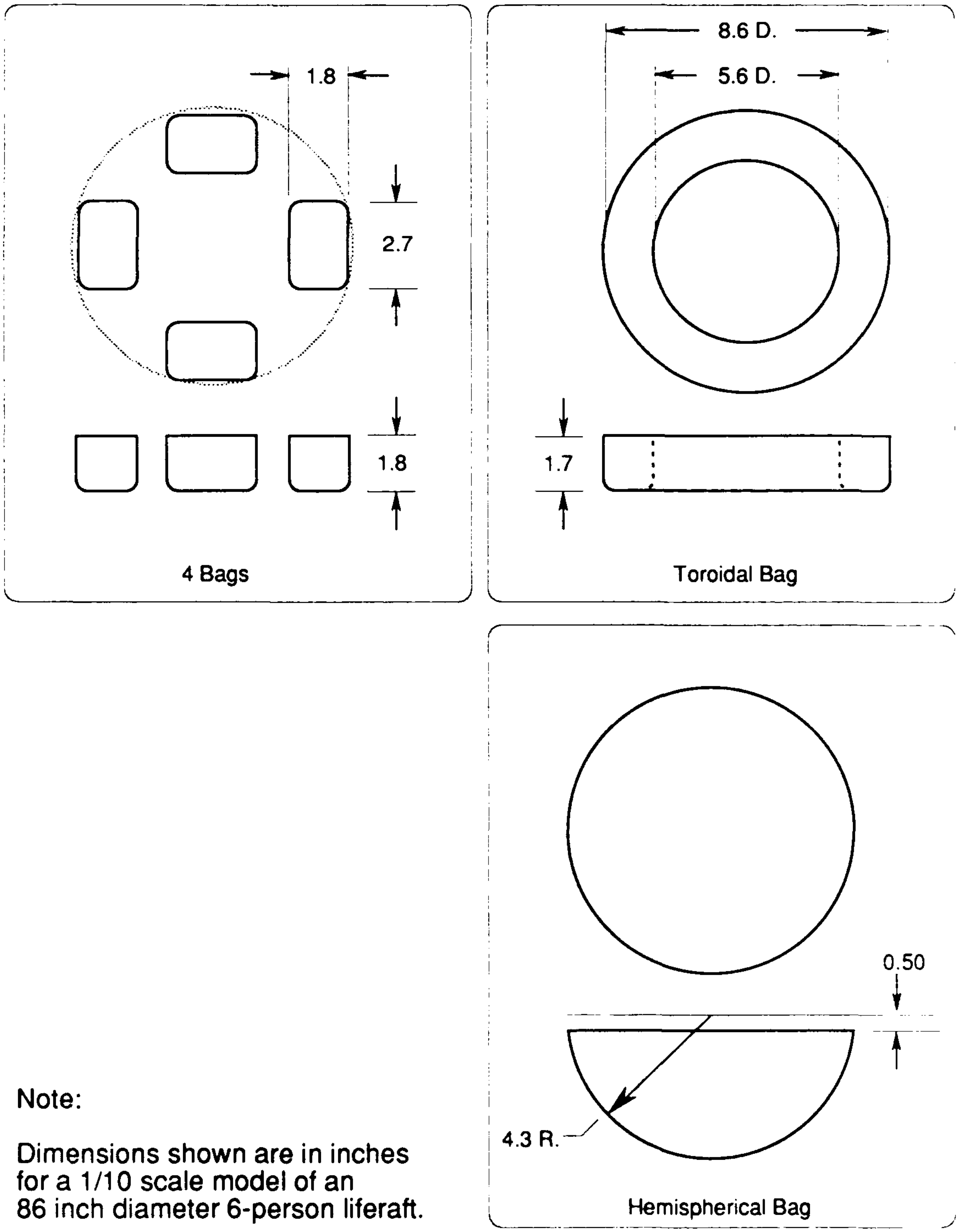


Figure 5. Life Raft Models

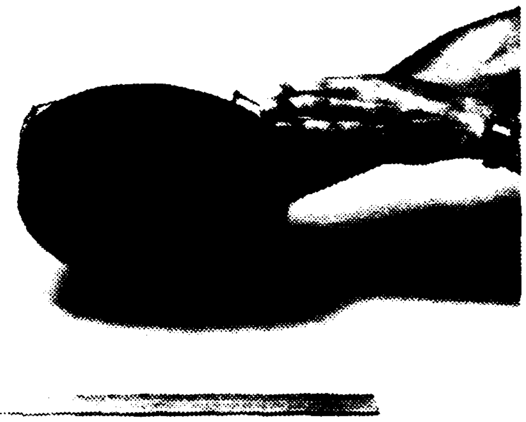


Note:

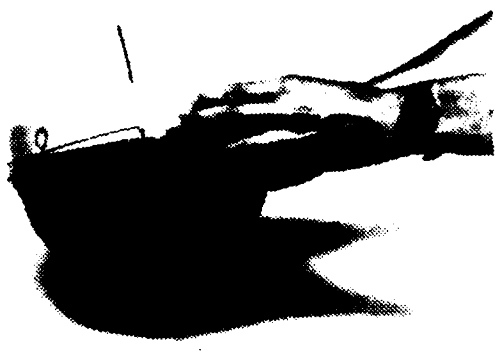
Dimensions shown are in inches for a 1/10 scale model of an 86 inch diameter 6-person liferaft.

Figure 6. Ballast Configurations

a. Four bags



b. Toroidal bag



c. Hemispherical bag

FIGURE 7. Ballast Configurations

was provided on the inside of the tank so that the position of the model could be established for each frame of the video.

In an effort to obtain a more accurate determination of the acceleration experienced by the occupants of the raft during a wave strike some test runs were recorded with a movie camera at a frame speed of 200 frames per second.

The velocity of the wind from the blower was measured with a hand-held turbine type wind meter.

THE WAVE

The wave generator provided a single breaking wave with a height of 1.7 ft. (0.5 m) and a velocity of 10.8 ft/sec (3.3 m/sec). For the 1/10 scale model this corresponds to a wave height of 17 ft. (5.2 m) and a velocity of 34 ft/sec (10.4 m/sec). For the 1/13 scale model the corresponding full-scale height would be 22 ft. (6.9 m) and the velocity 39 ft/sec (11.9 m/sec). Since the test wave was a single wave rather than a wave train there was no trough ahead of the wave. The breaking crest contained a large mass of water moving at wave speed. It is believed that this type of wave represents a very dangerous type of storm wave. A 1/24 scale sailing yacht model was violently rolled through 360 degrees when struck by the test wave as shown on Figure 8.

Photographs of the wave about to strike the raft model are shown on Figure 9. The energy to generate the wave was determined by the height of water in the hopper. This height was held at 93 in. (2.4 m) for these tests. A consistent, reproducible wave was generated.

Studies of pictures of storms at sea suggest that a typical storm wave is generally similar to the test wave generated in this facility rather than to the type of breaking wave that forms on a shelving beach. The deep water storm wave is in most cases a spilling breaker, i.e., a large wave with only the crest breaking. The slope of the wave ahead of the breaking crest is of the order of 30 to 45 degrees, whereas the beach wave is a plunging breaker with a concave face and with the maximum slope going beyond the vertical.

There is no assurance that a plunging breaker will not occasionally be encountered in an ocean storm. Therefore it would be desirable to also check the performance of the models in a facility where such a plunging breaker can by generated.

TEST PROCEDURE

For the initial tests the life raft model was placed in the tank at a series of different axial locations downstream of the wave generator. It was found that the most critical location was

FIGURE 8. Test Wave Striking 1/24 Scale Sailing Yacht Model

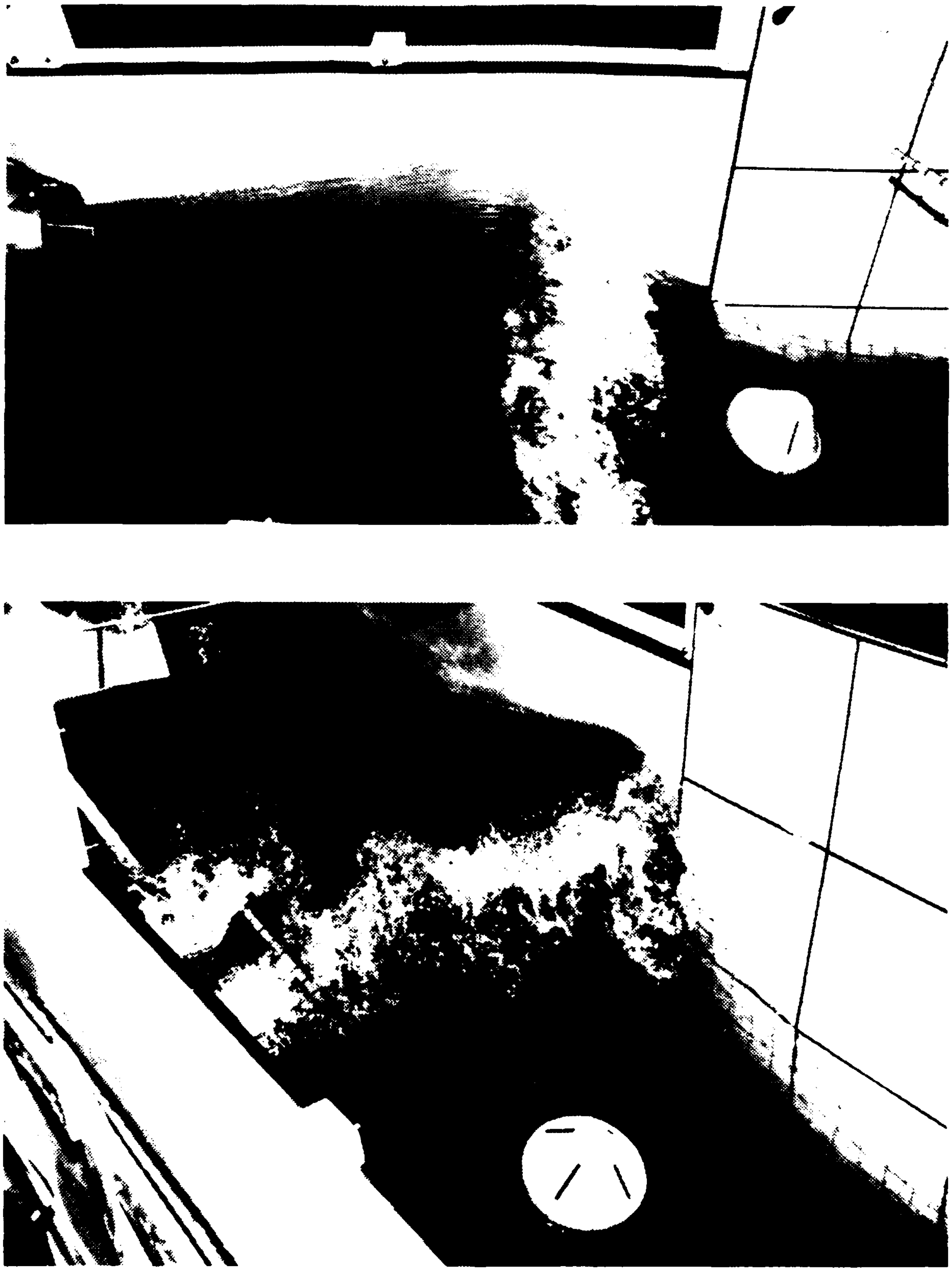


FIGURE 9. Test Wave About to Strike Model

just downstream of where the wave broke. At this location the unballasted raft would consistently capsize. For subsequent tests the raft models were placed at this location.

The raft model with the selected ballast configuration was placed in the tank and held in the correct position by a lightly loaded restraint system. A check was made to confirm that the ballast compartments were essentially full. The wave generator was actuated and the motion of the model recorded with a video camera. The blower was operated for certain runs to simulate storm winds.

A total of eight configurations were tested: 1/13 scale model with no ballast, with 4 ballast bags, with a toroidal bag, and with a hemispherical bag, and a 1/10 scale model with the same four ballast configurations. A log of all runs made is given in Appendix A.

TEST RESULTS

With no exceptions the unballasted raft was capsized by the breaking wave whereas the ballasted rafts were not capsized. This was true for all configurations of ballast: 4 bags, toroidal bag and hemispherical bag, for both 1/10 and 1/13 scale models and for no wind conditions and hurricane force surface winds.

The unballasted raft was immediately driven up to wave speed, capsized, and then propelled ahead of the dissipating wave crest. Figure 10 shows the model in the inverted position.

The ballasted models were also accelerated by the wave. The smaller 1/13 scale models were generally driven up to wave speed while the larger 1/10 scale models, particularly with the heavier toroidal or hemispherical ballast, would often penetrate the crest and not reach wave speed. Figure 11 shows the 1/10 scale model with hemispherical ballast. It will be noted that the breaking wave crest has passed the model.

With all three types of ballast, the model was so heavy that it would not rise quickly through the crest. When struck, the models were essentially submerged in the moving water. Generally they would be rolled up to an angle of 60 to 80 degrees but occasionally as high as 110 degrees. Then, as the crest dissipated they would rise up and right themselves. Figure 12 shows the 1/10 scale model with toroidal ballast. The model is almost completely submerged and has rolled up to an angle of 90 degrees. Repeated testing confirms that the model will not capsize in this situation.

Surface winds had no discernible effect on the behavior of the ballasted models. The capsize of the unballasted model was somewhat hastened by the presence of surface wind but the model would capsize without any wind.

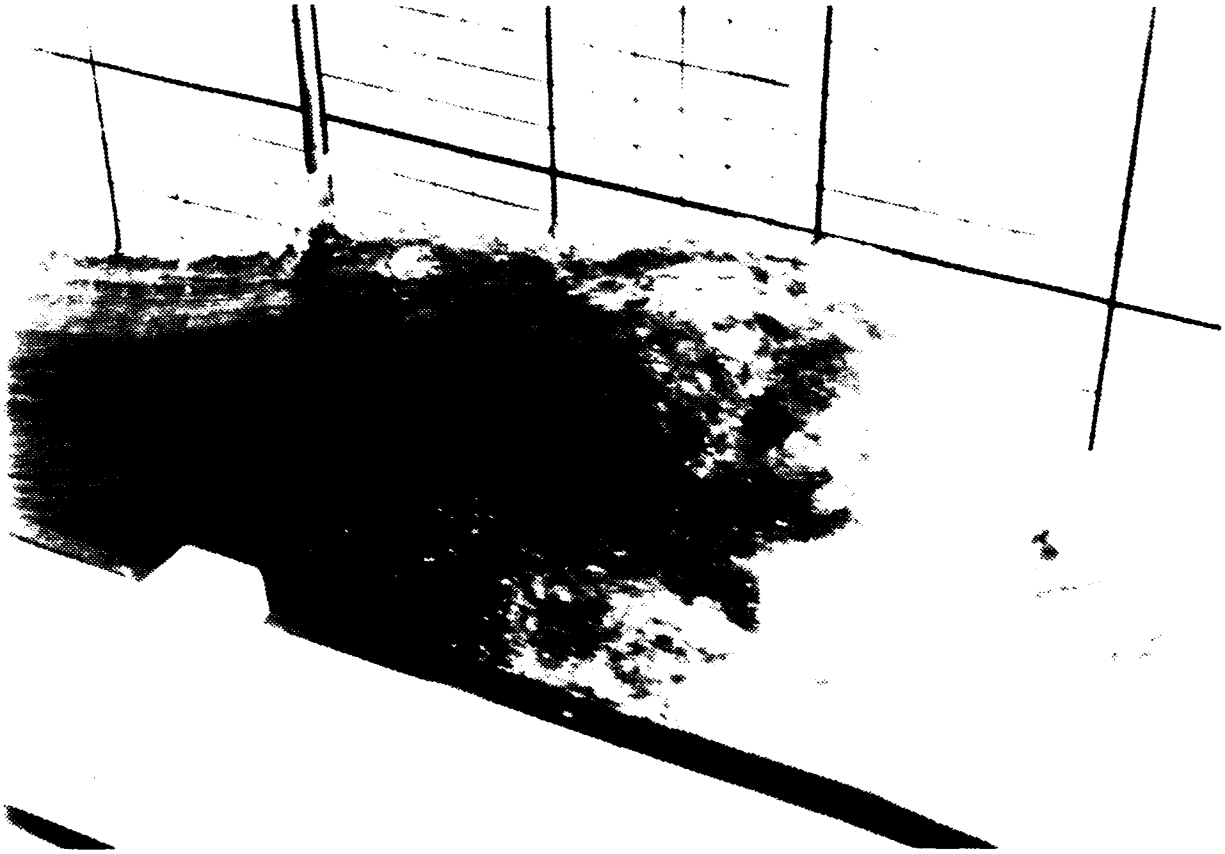


FIGURE 10. Breaking Wave Striking 1/10 Scale Unballasted Model
(Model in lower right is in inverted position)

FIGURE 11. 1/10 Scale Model with Hemispherical Ballast
(Note that wave crest has passed model)

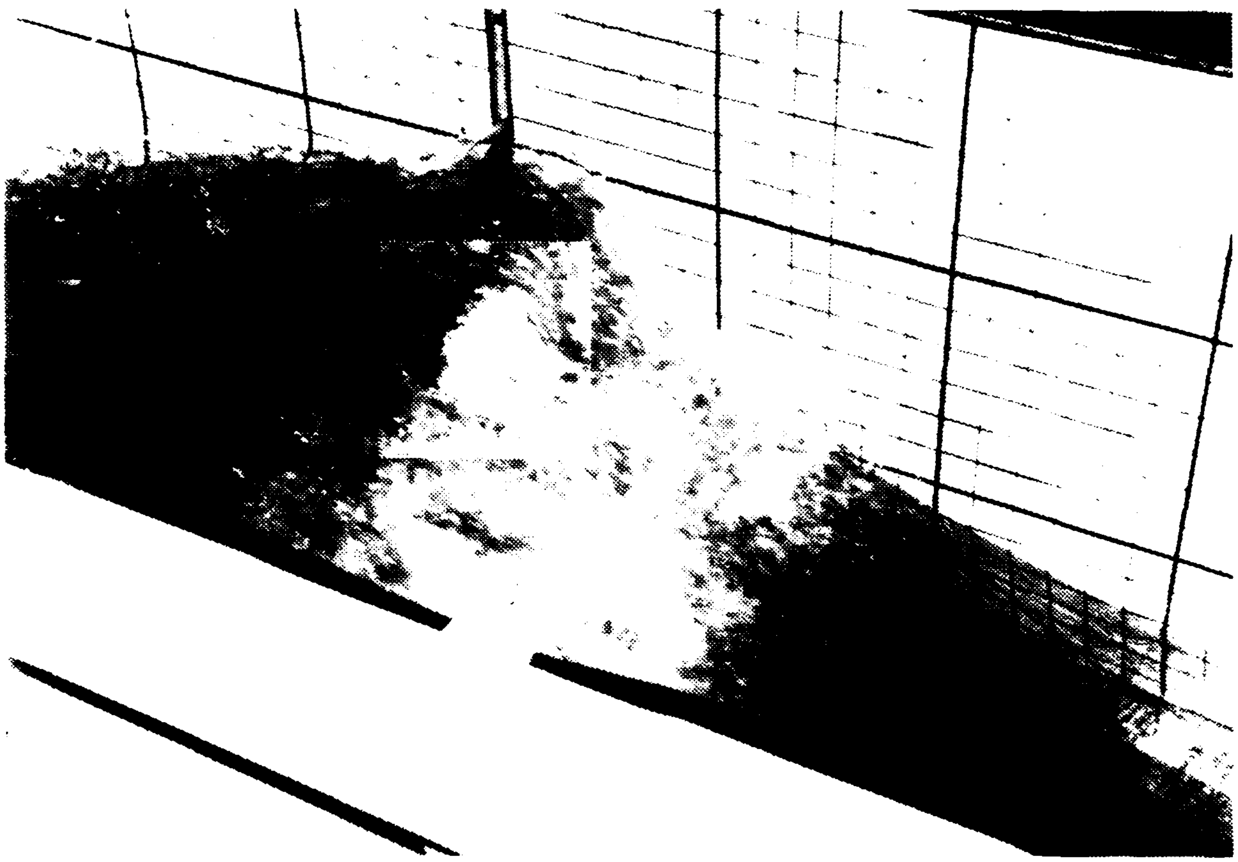


FIGURE 12. 1/10 Scale Model with Toroidal Ballast
(Note that model is essentially submerged by breaking crest)

SELF-RIGHTING CHARACTERISTICS

Simple tests were run to evaluate the self-righting characteristics of the ballasted rafts. The canopy was removed from the models for these tests since, for a 180 degree capsize, it is believed that in a full-scale event the canopy would be collapsed and flattened by the weight of the water in the ballast compartments.

The ballasted rafts were placed in a tank of water with no waves or wind. The self-righting behavior was checked for three angles of rotation from the horizontal position: 90, 135, and 180 degrees. The raft with the ballast compartments full was quickly rotated manually to the desired angle and then released. The subsequent motion was recorded on a video camera.

It was found that the raft rapidly righted itself from the 90 degree position with all three of the ballast configurations. However, only the hemispherical ballast bag would recover from the 135 and 180 degree positions. The 4 bag and toroidal configurations would recover from an angle somewhat higher than 90 degrees, possibly as high as 110 degrees.

The hemispherical bag recovered quickly from 135 and 180 degrees. A test was made with a significant portion of the water removed from the bag and the raft still recovered from the 180 degree inverted position. This characteristic of the hemispherical configuration appeared to be the result of two factors: first, the bag had greater volume and thus was heavier than the other configurations, and second, the bag would tend to slump over to one side when inverted thus providing an effective righting moment.

It should be noted that the total volume of the 4 ballast bags was chosen to be equal to the total volume of the buoyancy compartments in accordance with the proposed Coast Guard minimum requirements for ballast compartments volume. The volume of the toroidal bag was 1.6 times the volume of the buoyancy compartments and the volume of the hemispherical bag was 4 times the volume of the buoyancy compartments.

ACCELERATION FORCES ON THE RAFT OCCUPANTS

When the high velocity water in the breaking wave crest strikes a life raft the raft is rapidly accelerated. Often it is accelerated all the way up to wave speed. The resulting acceleration force might tend to throw the occupants and gear out of the raft or throw them around inside the raft possibly causing injury. An attempt was made to determine the influence of the water ballast compartments on the acceleration forces. Moving pictures were taken at 200 frames per second and the frame-by-frame displacement of the raft was measured. This procedure did not permit the acceleration to be measured with a high degree of

accuracy. However, it was determined that the unballasted raft experienced an acceleration of at least 2.3g and possibly significantly higher during a wave strike. The direction of the resulting force vector was toward the wave and at an angle of 20 to 40 degrees downward relative to the floor of the raft. With the ballast bags the tests show that the acceleration would be reduced by at least one half. It seems logical that the hemispherical configuration would experience a lower acceleration than the 4-bag configuration since the mass of water in the hemisphere is greater. However the test technique did not provide sufficient accuracy to confirm such an effect.

CONCLUSIONS

It is concluded that all three water ballast configurations are effective in preventing capsize when the model is struck by a wave of the size and shape used in this testing.

In comparing these tests with Reference 1 tests it is noted that in the Reference 1 tests both the unballasted and the 4-bag configurations were capsized while the toroidal and hemispherical were not. For the Reference 1 tests the 4-bag configuration had a smaller volume, 11.6% of the volume of the buoyancy compartments compared to a volume of 100% of the volume of the buoyancy compartment volume used in these tests. It may be concluded that 100% of the buoyancy compartment volume as specified in Reference 2 is an adequate minimum volume for water ballast bags.

Although this testing and Reference 1 tests indicate that water ballast compartments of the proper volume can prevent capsize without the use of a drogue, the Icelandic and British requirements specify the use of a drogue combined with small water ballast bags (Reference 3). Also recent testing by the Russians, Reference 5, supports the concept of a drogue combined with small ballast bags. It is recommended that the models used for the tests described in this report be modified to represent the requirements of Reference 3, i.e., a specific drogue and bag design, and that this combination be tested in the U.S. Coast Guard R&D Center facility.

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APPENDIX A

RUN LOG

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MARCH 9, 1989

TEST OBJECTIVE: Initial checkout of facilities and models. Vary height of water in hopper and depth of water in tank. For these runs, ballast dimensions were 4% undersize due to shrinkage of latex material.

Run	Model Scale/Config.		Capsize	Comments
1	None	-	-	Hopper 80" Depth 16" Did not break
2	1/13	Hemisphere	No	Hopper 80" Depth 19" Did not break
3	1/13	Hemisphere	No	Hopper 80" Depth 21" Did not break
4	1/13	Hemisphere	No	Hopper 93" Depth 21" Good breaking wave
5	1/13	No Ballast	Yes	Hopper 95" Depth 24" Good wave
6	None	-	-	Document Wave
7	None	-	-	Document Wave
8	1/13	Hemisphere	No	Hopper 93" Depth 24"
9	1/13	Hemisphere	No	Hopper 93" Depth 24"
10	1/13	Hemisphere	No	Door hinge deformed
11	1/13	Hemisphere	No	Wave not consistent
12	1/13	Hemisphere	No	Wave not consistent

JUNE 9, 1989

TEST OBJECTIVE: Models provided with new ballast compartments of the correct dimensions. Grid installed on side of tank so motion of models could be documented. Water height in hopper standardized at 93 inches and water depth in tank at 24 inches. Test to check new models and door repair.

Run	Model Scale /	Config.	Capsize	Comments
1	1/10	No Ballast	Yes	Good wave and capsize
2	1/10	No Ballast	Yes	
3	1/10	No Ballast	Yes	
4	1/10	4 Bags	No	Rolled to 90°
5	1/10	Toroid	No	
6	1/10	Hemisphere	No	
7	1/23	Sailboat	Yes	Abeam
8	1/23	Sailboat	No	Bow on
9	1/23	Sailboat	Yes	Stern on - pitchpole
10	1/23	Sailboat	Yes	Bow on - pitchpole

JULY 19, 1989

TEST OBJECTIVE: Determine axial distance from wavemaker at which model is most likely to be capsized.

Run	Model Scale/Config.		Capsize	Comments
1	1/10	No Ballast	No	4.5 ft. from door, model vertical but recovered
2	1/10	No Ballast	Yes	4.5 ft. from door, model vertical but recovered
3	1/10	4 Bags	No	4.5 ft. from door
4	1/10	4 Bags	No	4.5 ft. from door
5	1/10	Toroid	No	4.5 ft. from door
6	1/10	Toroid	No	4.5 ft. from door
7	1/10	Hemisphere	No	4.5 ft. from door
8	1/10	Hemisphere	No	4.5 ft. from door
9	1/10	Hemisphere	No	3 ft. from door
10	1/10	Hemisphere	No	6 ft. from door
11	1/10	Hemisphere	No	14 ft. from door

JULY 27, 1989

TEST OBJECTIVE: Use 16 mm movie camera at 200 frames per second to obtain more accurate data on dynamics of model when struck by breaking wave.

Run	Model Scale/Config.		Capsize	Comments
1	1/10	Hemisphere	No	
2	1/10	Hemisphere	No	
3	1/10	Toroid	No	
4	1/10	Toroid	No	
5	1/10	4 Bags	No	
6	1/10	4 Bags	No	
7	1/10	No Ballast	Yes	
8	1/10	No Ballast	Yes	
9	1/13	No Ballast	Yes	
10	1/13	Toroid	No	
11	1/13	Hemisphere	No	
12	1/10	No Ballast	Yes	Move camera back and start film 1 sec. earlier
13	1/10	4 Bags	No	
14	1/10	Toroid	No	
15	1/10	Hemisphere	No	
16	1/10	Hemisphere	No	Record with video camera

AUGUST 13, 1989

TEST OBJECTIVE: Repeat tests with blower to provide wind over surface of tank to simulate storm conditions.

Run	Model Scale/Config.		Capsize	Comments
1	1/10	No Ballast	Yes	Violently rolled
2	1/10	No Ballast	Yes	Same as previous
3	1/10	4 Bags	No	Rolled up to approx. 90°
4	1/10	4 Bags	No	Blower raised 6" above water
5	1/10	Toroid	No	Rolled up to approx. 80°
6	1/10	Hemisphere	No	Rolled up to approx. 20°
7	1/10	Hemisphere	No	Rolled up to approx. 45°
8	1/13	4 Bags	No	Rolled up to approx. 90°
9	1/10	4 Bags	No	Blower lowered towards water, higher wind velocity, rolled up approx. 80°
10	1/10	4 Bags	No	Model moved 1 foot downwind, rolled up approx. 100°

JULY 29, 1989

TEST OBJECTIVE: To determine self righting characteristics of raft with various ballast configurations. For these tests, the models were equipped with a canopy made of a rigid material. This is not considered realistic since in the actual case, with the raft inverted, the canopy would certainly deform and probably completely collapse due to the weight of the water ballast departments. The 1/10 scale model was used for all tests.

Run	Model Configuration	Self Right	Comments
1	Hemisphere	Yes	From 180°
2	Hemisphere	Yes	From 180°
3	Toroid	Yes	From 180°
4	Toroid	Yes	From 180°
5	4 Bags	Yes	From 180°
6	4 Bags	Yes	From 180°
7	No Ballast	Yes	From 90°
8	No Ballast	No	From 95°

OCTOBER 18, 1989

TEST OBJECTIVE: To determine the self righting characteristics of the models with the canopy removed. For these tests the canopy was replaced with a flat piece of plywood attached to the top of the raft. Model was initially held at given angle, then released.

Run	Model Configuration	Self Right	Comments
1	Hemisphere	Yes(3)	Model at 90° (three tests)
		Yes(3)	Model at 180° (three tests)
		Yes(3)	Model at 135° (three tests)
		Yes(2)	Partially filled ballast, Model at 180°
2	Toroidal	Yes(2)	Model at 135° (7 tests)
		No(5)	
		Yes	Model at 90°
		No	Model at 180° (2 tests)
3	4 Bags	Yes(3)	Model at 90° (3 tests)
			No(3) Model at 135°
			No(2) Model at 180°
4	No Ballast	No(2)	Model at 180°
		Yes(2)	Model at 90°